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(54) **Endovascular stent with coating comprising tacrolimus**

Endovaskulärer Stent mit Takrolimus enthaltender Beschichtung

Stent endovasculaire avec un revêtement comprenant du tacrolimus

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Description

Field of the Invention

[0001] The invention relates generally to stents and more particularly to a drug delivery endovascular stent which delivers a specific immunosuppressant drug to the stent treatment site.

Background of the Invention

[0002] Stents are a widely used adjunct to coronary artery intervenfions. After an angioplasty or other intervention, a stent may be introduced to the treatment site to support the wall of the artery.

[0003] The principle problem with stent usage is a reclosure process called restenosis. The problem of restenosis is widely recognized. It appears from research that the mechanisms for restenosis after a balloon procedure differs in detail from the healing processes associated with stent placement.

[0004] The biological reactions associated with the use stents causes a cascade of cellular growth and proliferation. The mechanical action of the stent against the artery wall (spring back) and the introduction of the foreign substance into the body results in an inflammatory response which gives rise to signaling molecules called cytokines which mediate a variety of biologic processes. Although the magnitude and course of the inflammatory response varieswidely among patients, the body isolates the foreign material of the stent by encapsulating it with cell growth. Consequently a pseudo intima will be produced on the surface of the stent. In general the propagation of a smooth muscle tissue pseudo intima is desirable, however in some patients the proliferation of smooth muscle cells and their conversion to secretory muscle cells results in reclosure of the vessel within a short period of time. Although this is a normal response to the insertion of a foreign body, given the location of the stent it results in severe clinical problems. Other short term complications exist as well including acute thrombosis. The delivery of anti platelet drugs and other thrombolytic drugs have been proposed to treat this near term type of reclosure.

[0005] Several efforts have been made to prevent or delay the longer term restenosis process. One approach has been to implant radioactive stents where the local emission of beta radiation inhibits hyperplasia. Although intra-coronary radiation is effective at preventing restenosis this grossly interferes with the healing process previously described and can lead to secondary complications such as edge restenosis and late thrombosis. One example of this stent technology is known from US Patent 5,871,437 to Alt. This reference teaches the use of multiple coating on the stent substrate. One coating carries a beta emitter while other coatings deliver a anticoagulation drug.

[0006] Another approach to the treatment of acute thrombosis in stent treatments is discussed in US Patent 5,788,979 to Alt et al. The stent according to this invention uses a biodegradable coating to release a controlled amount of a therapeutic agent such as an a anticoagulant, anti-thrombogenic, or antistenotic drug. The biodegradable coating provides a local release of drug which improves the bio-compatibility of the stent and reduces inflammation and the hyperplasia processes. The objective or these different methods is to interfere with and control the proliferation of the smooth muscle cells.

[0007] Although the various coated stents improve the restenosis rates for some patients, a fully bio-compatible stent remains an elusive problem as the factors of local thrombus formation, vessel injury and inflammation interact in complex and individually variable ways. For these reasons re-occlusion and restenosis problems are difficult to manage in a clinical setting. Restenosis remains a significant risk for patients.

[0008] It is an object of the invention to provide a stent which hinders restenosis and garantuees a normal wound healing at the treatment site.

[0009] This object is solved according to the invention by the features of claim 1.

[0010] Further embodiments are disclosed in the subclaims.

[0011] In contrast to the prior art, the stent of the present invention delivers an effective dose of the immunosuppressant drug tacrolimus to the stent treatment site. The tacrolimus is delivered at a rate and in a concentration that both encourages proliferation of smooth muscle cells of the contractile type, while these cells are responsible for the restenotic process, smooth muscle cells of the contractile type are mandatory for regular and fast wound healing. This is the major difference compared with other cytostatic drugs and other immnunosuppressants, such as sirolimus, for tacrolimus only slightly inhibits the proliferation of cells but limits conversion of such cells to the secretory type muscle cells. This method and approach differs from the prior art cytostatic techniques where Taxol and related drugs are used in an overall strategy to interfere with and delay the healing response.

[0012] In accord with the present invention a stent delivers tacrolimus to the cells proliferating on the surface of the stent. The stent forms a primary structure and the coating is a secondary process. In general it is preferred to use a polymer coat but surface modification of the stent itself to create a drug delivery surface is possible though not preferred. Also a mere coating of the stent by a sufficient amount of the drug such as 40 to 200 mg drug directly attached to the preferably roughened surface of the stent is conceivable.

[0013] The preferred device delivers drug by elution from a polymer matrix applied as a coating to the stent. The polymer matrix may be permanent and non biodegradable or it may be biodegradable. An example of a suitable biodegradable material is polylactic acid (PLA). Examples of more permanent matrix materials includes;

polyethylene; vinyl acetate and medical polyurethanes and silicone rubber. Other biodegradable and non biodegradable materials are contemplated within the scope of the inventions well. The primary requirement is the formation of a biocompatible matrix to allow elution of the tacrolimus.

[0014] The localized and selective delivery of the tacrolimus and tacrolimus containing compounds encourages endothelization of the stent with smooth muscle cells and other endothelial cells and discourages the proliferation and conversion of such cells to secretory smooth muscle cell types.

[0015] The beneficial effect of tacrolimus and its analogues is unknown in this context and the drug is not indicated for or labeled for use in cardiovascular interventions.

[0016] Although arterial endovascular and specifically coronary interventions are an important application for this invention it should be recognized that other biomedical devices and device locations, sizes and drug concentrations are contemplated within the scope of the invention. It must also be recognized that additional features and structures may be added to the invention without departing from the scope of the invention.

Brief Description of the Drawings

[0017] Throughout the figures of the drawing like reference numerals represent identical structure, wherein:

Fig. 1 shows a stent being delivered to a treatment site; and

Fig. 2 shows a stent with the preferred coating applied.

[0018] Fig. 1 shows a stent 10 which has been crimped onto an angioplasty balloon 12. The assembly 14 is being delivered to a treatment site 16 in an arterial vessel 16. In a typical intervention the stent 10 will be made of a metal mesh and this primary structure will be mechanically deformed onto a balloon after it has been coated with the drug. After insertion into the treatment site 16 the stent 10 will be deployed by expanding it into the tissues at the treatment site. The secondary coating on the surface of the primary structure will be in contact with the tissue at the treatment site and the stent will be exposed to a continuous flow of blood at the site.

[0019] Fig. 2 shows a partial cross section of a segment of the stent. 10 The metal substrate 20 provides the mechanical characteristics for the stent and is the primary structure as is well known in this art. As seen in the figure the stent 10 is a hollow tube having open ends typified by open end 24 and a side wall substrate 20 with multiple apertures typified by aperture 26.

[0020] The secondary coating 22 is preferably a biodegradable polymer such as PLA carrying a concentration of the drug tacrolimus. The preferred approach is to dissolve the Tacrolimus in the selected polymer and dip coat the stent. In this preferred process the tacrolimus is uniformly distributed in the coating. It is important to note that other approaches may be adopted as well. For example the surface of the stent may be modified to exhibit porosity. This matrix may be considered as secondary coating and it maybe loaded or filled with tacrolimus or a tacrolimus contains compound in another operation.

Example

[0021] The following protocol details an illustrative proposed test stent according to the invention.

[0022] Approximately 40 mg of R203, a polylactic acid of a molecular weight of 30 kDa, is dissolved in 0.6 ml chloroform together with 10 mg of tacrolimus. The resulting solution yields a weight-related content of 20 % of tacrolimus in the coating. Contents between 5 and 30% by weight are possible.

[0023] The stents are dip-coated at reduced temperate in several steps in order to apply an approximately 10 µm thick coating on the stent surface. The thickness of the coating (or roughness of the stent surface) depend on the dimensions of the stent and may be greater for example for stents implanted in thick blood vessels.

[0024] Next the stents are crimped on a balloon. When used in a patient the stent will be expanded into a vessels of a patient to a maximum diameter of 4.5 mm. The expansion of the stent places the polymer matrix which is acting a secondary coating in contact with the tissues at the site of stent placement. Stents proposed for use are conventional in design and are commercially available from InFlow Dynamics (InFlow Starflex Stent Design).

Expected mechanism of operation and interaction with the body

[0025] Tacrolimus was discovered in 1984 in the culture medium of a bacterium that was detected in the soil in Japan. The bacterium was called Streptomyces tsukubaensis, and has shown to have interesting properties. Initially it was assumed to belong to the group of the macrolide antibiotics such as erythromycin.

[0026] Tacrolimus has a molecular weight of 822 Da, it is a white crystalline powder and it has both a lipophilic and strong hydrophobic behavior which are exploited in the invention. It is soluble in chloroform, ethylacetate acetone, and ethanol, and is practically insoluble in water. This drug is available from Fujisawa Inc. of Japan.

[0027] The approved indications for the drug vary between countries. In the US, tacrolimus is currently approved for the use in the prophylaxis of organ rejection in patients receiving liver or kidney transplant. In UK and Canada, tacrolimus is indicated for primary therapy and rescue therapy for graft rejection resistant to conventional immunosuppressive regimen and several Euro-

pean countries have approved the drug for heart transplantation.

[0028] The applicant has observed in restenosis that the infiltration of lymphocytes, macrophages, and plasmacells end in matrix production of smooth muscle cells.

[0029] It is believed that the production of T-helper cells and the production of cytokines are an important mechanism in the immunoresponse to a foreign body. If the stent surface is recognized as a foreign body by the CD4 identifiable helper cells (T_{H1}, T_{H2}), this induces a T-cell proliferation. The helper cells produce various cytokines such interleukine 2, interferon y (IFNy) that cause an activation of killer and cytotoxic T-cells as well as polynuclear granulocytes and mastcells. The mastcells themselves produce interleukine 1 and 2, which also enhance the proliferation of the T-cells. This response results in cellular cytotoxicity and antibody creation.

[0030] Interferon y enhances the expression of intercellular adhesion molecules (ICAM1), that increases the adhesion of T-cells to the endothelial cells. This also effects a local thrombus formation on the endothelial cells and increases the endothelial permeability.

[0031] It appears the interleukine 8 especially promotes the adhesion and transepithelial migration of T-cells into the neointimal build-up. In transplant rejections, an increase in interleukine 8 production precedes the rejection of the organ by several days. In summary, the rejection of a foreign body is carried forward primarily by T lymphocytes, monocytes, macrophages, and killercells that are upregulated by a wide variety of cytokines such as interleukine 2, 4, 5, 6, 8, and 10, interferon γ, and TNFα.

[0032] When a T-cell recognizes the antigenic foreign surface then, upon activation, phospholipases (PLC) induce the generation of inositol-triphosphate (IP_3), a primarily calcium dependent signal transduction. Calcineurin diphosphorylizes the nuclear factor of activated lymphocytes in the cytoplasma (NF-ATC) and induces its translocation into the nucleus (NF-AT).

[0033] At the nucleus, this complex induces the transcription of interleukines 2, 3, 4, 5, and 8 genes as well as the transcription of TGFβ and of the tumornecrosis factor α. The transcription of the specific cytokine genes into mRNA results in the production of the respective cytokines by the T-cell.

[0034] Tacrolimus has a specific binding site in the cytoplasma. This binding protein is called FKBP-12. The binding of tacrolimus to this receptor binds to the calcineurine and inhibits the calcium dependent signal transduction. By this way, it inhibits the translocation of the cytoplasmatic NF-ATC from the cytoplasma into the nucleus and thereby the expression of the above mentioned cytokines.

[0035] TGFβ is not only released by T lymphocytes, but also by activated endothelial cells. Endothelial cells have a wide range of purposes and action. Aside from the production of the nitrogen monoxide NO, that inhibits vascular smooth muscle cell proliferation, endothelial cells are capable upon stimulation to produce also growth factors such as insuline-like growth factor (IGF1), basic fibroblast growth factor (bFGF), interleukine 6, and especially transforming growth factor β. In addition, if upon stimulation of interleukine 4, tumornecrosis factor α, and interferon γ the expression of ICAM-1 increases, the endothelial layer is more permeable to the cytokines and allows them to penetrate through the endothelial layer.

[0036] TGFβ has the capability to transit smooth muscle cells from their contractile state into its proliferative form. In this form, the cells are very secretory and produce a wide variety of intercellular matrix, among them various collagens and proteoglykanes.

[0037] Applicant believes that the primary action of tacrolimus is that it acts both as a suppressor of the inflammatory reaction against the foreign stent body and as a competitive inhibitor at the FKBP-12 receptor of smooth muscle cells and prevents them to enter the secretory state. Applicant believes that the important factor to be addressed in stent coatings is the immunoresponse toward the foreign body of the stent.

[0038] In a recent study, the different inhibitory effects of immunosuppressive drugs on human and rat aortic smooth muscle cells and endothelial cell proliferation were studied. This trial revealed that tacrolimus very modest antiproliferative properties on vascular cells. This means that the normal wound healing response is not compromised, but the transition to the secretory smooth muscle cell type that is responsible for the restenosis build up is practically totally inhibited. This is the major difference between this and other immunosuppressive drugs that inhibit all normal wound healing responses.

[0039] Also methylprednisolone showed a gradual inhibition over a broad concentration interval in rat and human smooth muscle cells, but not of human endothelial cells.

Dosage

[0040] Since only a limited amount of drug can be coated onto the surface of a stent, the most potent drug should be used. In clinical practice, the dosage for tacrolimus normally is a range of 0.04 - 0.06 mg/kg/day, if given intravenously. This means about 4 mg per day for a 75 kg patient are applied, a level in the whole blood of 10-20 ng/ml is the primary goal.

[0041] The dosages of cyclosporine and of mycophenolic acid which are used for immunosupression are 10 to 100-fold higher in order to achieve similar effect.

[0042] A second aspect makes tacrolimus highly superior over cyclosporine, is its dual action on the cytokine inhibition. While cyclosporine also inhibits the cytokine release from T-cells, it has not the competitive inhibitory effect of TGFβ in smooth muscle cells, which is according to the hypothesis of this study the major

action of arteriosclerosis and restenosis associated with the foreign body implant of a stent.

[0043] Tacrolimus is a lipophilic substance which is practically insoluble in water. Therefore, its distribution in the blood is primarily intracellular in red blood cells, in the plasma it is bound to α-1 sour glycoproteins and albumins. This means, that if coated to a stent the concentration in the cells will be high, while the solution into plasma is low, resulting in a high local concentration.

[0044] Previous studies with PLA-coating have shown that a thickness of 10 pm of PLA on the stent surface is favorable. This means, that on a 16 mm long stent on average 500 pg of carrier are applied by means described previously. In order not to compromise the physical characteristics of such a stent coating, a maximum of 20 % of drug can be incorporated into the carrier. This means, that roughly 100 pg tacrolimus to a stent can be applied. Assuming a release over more than 10 days, the total dosage released is less than 1/1000 of the dosage given intravenously. Assuming that the majority is not released into the blood and that tacrolimus has a halflife of 12 hours, the systemic dosage released from the stent coating is 105~6 below that what is needed for a systemic action.

[0045] Assuming a release similar to other drugs incorporated into the PLA carrier a minimum intracellular level of tacrolimus in the therapeutic range of 5 - 20 ng/ml tissue can be achieved in the adjacent wall.

[0046] The degradation of the PLA matrix has been tested in the past and described. In principle, at 37° C also a magnetic stirrer tests the weight loss of stents in a saline solution. PLA degrades by hydrolysis to lactic acid. Previous calculations have shown, that if the entire amount of polymere was immediately degraded, this would result in roughly 5 pmol of lactic acid, that would be diluted in an average blood volume of 71. This would respond to a burden of lactic acid of about 10^{-6} µmol/ml lactate, well below the level of lactate present in blood after strenuous exercise (2-4 µmol/l).

Non Bio-resorbable Coating

[0047] Non digestible coatings can be used as well. In addition to surface modification of the metal of the stent several polymer coats are contemplated. In this embodiment the polymer coating acts as an alternative to the PLA and the pharmo-kinetics related to dose administration must be tailored to provide a therapeutic dose based on the composition of the polymer. It is expected that the drug will be released through a diffusion process over a number of days. The polymer matrix should be tailored to achieve a therapeutic release. It is expected that polyurethanes and polyethylene and similar plastics will be useful in this application. Also the mere adhesion of the drug without a carrier to the surface of the stent is feasible, especially if the surface of the stent is rough.

[0048] The invention provides a method of treating a blood vessel with the following steps:

inserting a stent into said vessel;
expanding said stent into contact with vessel walls;
eluting tacrolimus from the stent into the site of the stent.

[0049] This method is advantageous in so far as the restenotic process following implantation of a stent into the artery of the human body is inhibited without compromising the normal wound healing. The method inhibits the cell proliferation through the mechanism of selectively inhibiting the foreign body induced inflammatory response and the transition of smooth muscle cells from their contractile state to a proliferative state and secretory state.

[0050] The tacrolimus is applied to the surface of the stent either directly or is preferably uniformly distributed in or on a coating of the stent.

Claims

1. An endovascular stent comprising:

   a hollow tube having open ends and a sidewall with multiple aperatures forming a primary structure, whereby said hollow tube can be deformed to position the hollow tube in a vessel;

   a secondary coating on said primary structure; and

   a quantity of tacrolimus located within said secondary coating, the quantity being tailored and adapted to achieve a localized concentration within the vessel at the stent implantation site to allow normal wound healing to take place, while concurrently limiting an inflammatory response, that would result in restenosis, at said site.

2. A stent of claim 1, wherein said localized concentration is predetermined to produce a rate of delivery of tacrolimus at the stent implantation site to prevent a transformation of smooth muscle cells at said site from a contractile cell type to a matrix producing secretory cell type.

3. A stent according to claims 1 or 2, whereby the secondary coating containing tacrolimus in a polymer matrix is tailored and adaped for therapeutic release of tacrolimus from the stent coating at the deployment site in a concentration and at a rate adequate to achieve, concurrently, (i) an immuno-suppressive response sufficient to inhibit rejection of the stent by the body, (ii) a anti-inflammatory response sufficient to inhibit stenosis at said site, and

(iii) an anti-proliferative effect insufficient to compromise the body's natural wound healing response at said site.

4. The stent of any preceding claim, wherein said secondary coating is biodegradable.

5. The stent of any of claims 1 to 3, wherein said secondary coating is non biodegradable.

6. The stent of any preceding claims, wherein said tacrolimus is uniformly distributed in said secondary coating.

7. The stent of claim 4, wherein said secondary coating contains the bioresorbable polymer polylactic acid.

8. The stent of claim 7, wherein the concentration of tacrolimus in the secondary coating yields a dose of about 10 to 20 nm of tacrolimus per each ml of blood volume.

9. The stent of any of the preceding claims, wherein the amount of tacrolimus is in a range of 5 to 30 % by weight with respect to the secondary coating, preferably in a range of 10 to 20 %.

Patentansprüche

1. Endovaskulärer Stent mit:

einem hohlen Rohr mit offenen Enden und einer Seitenwand mit einer Vielzahl von Öffnungen, das eine Primärstruktur bildet, wobei das hohle Rohr deformiert werden kann, um das hohle Rohr in einem Gefäß zu positionieren;

einer sekundären Beschichtung auf der Primärstruktur; und

einer Menge von Tacrolimus, die in der sekundären Beschichtung gelegen ist, wobei die Menge bemessen und abgestimmt ist, um eine lokale Konzentration innerhalb des Gefäßes an dem Implantationsort des Stents zu erreichen, um eine normale Wundheilung zu ermöglichen und gleichzeitig an diesem Ort eine Entzündungsreaktion zu verhindern, die in einer Restenose resultieren würde.

2. Stent nach Anspruch 1, wobei die genannte lokale Konzentration vorbestimmt ist, um eine Abgaberate von Tacrolimus an dem Implantationsort des Stents zu erzeugen, sodass eine Transformation von weichen Muskelzellen an diesem Ort von einem kontraktilen Zelltypus zu einem matrixproduzierenden sekretorischen Zelltypus verhindert wird.

3. Stent nach Anspruch 1 oder 2, wobei die sekundäre Beschichtung, die Tacrolimus in einer Polymermatrix enthält, bemessen und abgestimmt ist für eine therapeutische Abgabe von Tacrolimus aus der Stentbeschichtung an dem Einsatzort in einer Konzentration und mit einer adäquaten Rate, um gleichzeitig

i) eine immuno-unterdrückende Reaktion zu erreichen, die ausreichend ist, die Abstoßung des Stents durch den Körper zu verhindern,

ii) eine anti-inflammatorische Reaktion zu erreichen, die ausreichend ist, eine Stenose an dem Ort zu verhindern, und

iii) eine anti-proliferative Wirkung zu erreichen, die ausreichend ist, um die natürliche Wundheilungsreaktion an diesem Ort nicht zu gefährden.

4. Stent nach einem der vorhergehenden Ansprüche, wobei die sekundäre Beschichtung biodegradierbar ist.

5. Stent nach einem der Ansprüche 1 bis 3, wobei die sekundäre Beschichtung nicht biodegradierbar ist.

6. Stent nach einem der vorhergehenden Ansprüche, wobei Tacrolimus in der sekundären Beschichtung gleichmäßig verteilt ist.

7. Stent nach Anspruch 4, wobei die sekundäre Beschichtung das bioresorbierbare Polymer Polylactidsäure enthält.

8. Stent nach Anspruch 7, wobei die Konzentration von Tacrolimus in der sekundären Beschichtung in einer Dosis von etwa 10 bis 20 nm von Tacrolimus pro ml des Blutvolumens vorliegt.

9. Stent nach einem der vorhergehenden Ansprüche, wobei die Menge von Tacrolimus in einem Bereich von 5 bis 30 Gewichtsprozent im Hinblick auf die sekundäre Beschichtung liegt, vorzugsweise in einem Bereich von 10 bis 20%.

Revendications

1. Stent endovasculaire comprenant :

un tube creux ayant des extrémités ouvertes et une paroi latérale munie de multiples ouvertures formant une structure primaire, d'où il résulte que le tube creux peut être déformé pour dis-

poser le tube creux dans une enceinte ;
un revêtement secondaire sur la structure primaire ; et
une quantité de tacrolimus disposée dans le revêtement secondaire, la quantité étant dosée et adaptée pour obtenir une concentration localisée dans l'enceinte au niveau du site d'implantation du stent pour permettre qu'une cicatrisation normale de blessure prenne place tout en limitant une réponse inflammatoire qui entraînerait une resténose au niveau dudit site.

2. Stent selon la revendication 1, dans lequel la concentration localisée est prédéterminée pour produire un taux de fourniture de tacrolimus au niveau du site d'implantation du stent propre à empêcher une transformation de cellules musculaires lisses au niveau du site d'un type de cellule contractile à une matrice produisant un type de cellule sécrétoire.

3. Stent selon la revendication 1 ou 2, dans lequel le revêtement secondaire contenant du tacrolimus dans une matrice polymère est dosé et adapté pour une libération thérapeutique de tacrolimus depuis le revêtement du stent au niveau du site de déploiement en une concentration et à un taux propre à obtenir simultanément (i) une réponse immunosuppresseuse suffisante pour éviter un rejet du stent par le corps, (ii) une réponse anti-inflammatoire suffisante pour inhiber une sténose au niveau dudit site, et (iii) un effet anti-prolifératoire insuffisant pour compromettre une réponse de cicatrisation de blessure naturelle du corps au niveau dudit site.

4. Stent selon l'une quelconque des revendications précédentes, dans lequel le revêtement secondaire est biodégradable.

5. Stent selon l'une quelconque des revendications 1 à 3, dans lequel le revêtement secondaire est non biodégradable.

6. Stent selon l'une quelconque des revendications précédentes, dans lequel le tacrolimus est uniformément réparti dans le revêtement secondaire.

7. Stent selon la revendication 4, dans lequel le revêtement secondaire contient un acide polymère polylactique biorésorbable.

8. Stent selon la revendication 7, dans lequel la concentration de tacrolimus dans le revêtement secondaire fournit une dose d'environ 10 à 20 mm de tacrolimus par ml de volume sanguin.

9. Stent selon l'une quelconque des revendications précédentes, dans lequel la quantité de tacrolimus est dans une plage de 5 à 30 % en poids par rapport au revêtement secondaire, de préférence dans une plage de 10 à 20 %.

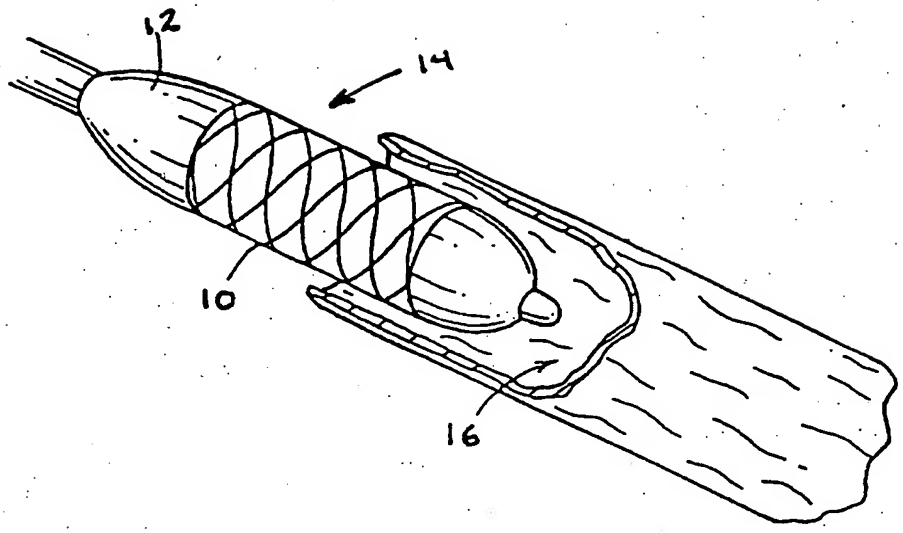

FIG. 1

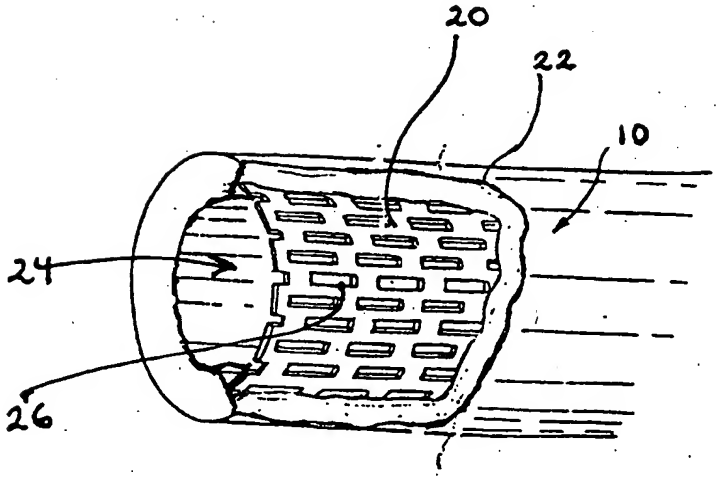

FIG. 2